Development of Probabilistic Convective Weather Forecast Threshold Parameter for Flight Routing Decisions

Kapil Sheth
NASA Ames Research Center, Moffett Field, CA

Thomas Amis
National Weather Service, Ft. Worth, TX

Sebastian Gutierrez-Nolasco
UC Santa Cruz, Moffett Field, CA

Banavar Sridhar
NASA Ames Research Center, Moffett Field, CA

Daniel Mulfinger
NASA Ames Research Center, Moffett Field, CA

Corresponding author address: Kapil Sheth, NASA Ames Research Center, MS 210-15
Moffett Field, CA.
E-mail: Kapil.Sheth@nasa.gov

Abstract

This paper presents a method for determining a threshold value of probabilistic convective weather forecast data. The threshold represents the bounding severe weather forecast probability value that most aircraft are observed to avoid. Given a probabilistic prediction of weather, this value can be used by dispatchers for flight planning; and by air traffic managers to reroute streams of aircraft around convective cells. Both, the intensity and ceiling of the forecasted weather were synchronized with air traffic data in a simulation to derive the probability threshold. The main contribution of this paper is to provide a method to compute probability threshold parameters using an experimental 6-hour probabilistic convective weather forecast product. Air traffic and weather data for a four-month period during the summer of 2007 were used to compute the parameters for the continental United States. Threshold values for each of the 20 Air Route Traffic Control Centers were also computed. Additional details are presented for seven high-altitude Sectors in the Ft. Worth Center. The results are shown for different altitudes, times of day, aircraft types and airspace users.

Airline dispatchers and traffic managers are involved in flight operations to avoid specific areas of convective activity. A secondary contribution of this paper is to describe a simple approach to utilize the threshold parameter for flight routing decisions in Ft. Worth Center during convective weather events. This approach is similar to national severe weather routes currently used by the FAA, except in a Center-based, local event. The paper presents results for contrasting the nationwide reroutes and the local strategy. The results suggest that such an analysis capability could save fuel and reduce air traffic delays.

1. Introduction

Based on air traffic delay results from the Federal Aviation Administration's (FAA) Operations Network (OPSNET) data, more than 70% of the National Airspace System (NAS) reportable delays are attributed to convective weather. Furthermore, a study by Sridhar, et al. (2007) indicated that a small number of Air Route Traffic Control Centers (ARTCCs or Centers) experience a majority of the weather impact. The current deterministic weather prediction in tactical (next 2 hours) timeframe is used for air traffic operations. Current operational strategies to route air traffic around convective weather systems, such as the FAA's Severe Weather Avoidance Plan (or Playbook Routes), use pre-established routes to ensure predictable and safe circumvention of convective weather zones. These national strategies may force aircraft to take large deviations, even if the aircraft were unlikely to encounter convective weather, and usually impose additional workload on Centers not directly affected by the convective weather system. It is widely accepted that the state of weather forecasting in strategic (2-8 hours) time frame needs improvement for longer-term flight planning (Clifford 2003, Fahey, et al. 2006). Also, some work has been done to tactically reroute individual aircraft around weather cells (Grabbe, et al. 2008 and Sridhar, et. al. 2002), little work has been done to strategically route flights for the Center level weather events.

In the absence of improved forecast, considerable research is being conducted to develop improved weather products and to determine how to make better use of probabilistic data for improved flight planning. The NCAR has recently released a National Weather Forecast Product (NCWF) that provides 1, 2, 3, 4, 5, and 6 hour forecasted probabilistic weather contours. An overview of the weather data needs and benefits to various participants in Air Traffic Management (ATM) along with available products can be found in Fahey, et al. (2006). Past research has focused on the concept of operations for strategic traffic flow management, including how weather data can be integrated for efficient traffic management initiatives (Hoffman, et al. 2004, Nilim and El Ghaoui, 2004, and Song, et al. (2008)). A model of predicting likelihood of flight deviation and pilot behavior around a convective storm is available in DeLaura and Evans (2006). Chan, et al. (2007). More recently Matthew and DeLaura (2010), validate that pilots deviate when the avoidance model predicts 80% or higher likelihood of deviation for the analyzed altitudes. Weygandt and Benjamin (2004), and Megenhardt, et al. (2004) present probabilistic weather forecast generation method, and identify a need for the relevance of these forecasts for aviation use. Steiner, et al. (2008) looked at probabilistic air traffic management decisions by considering ensemble (and consequently, probabilistic) forecasts for developing traffic flow evolution scenarios. Another study by Wanke and Greenbaum (2007) presents the probabilistic decision making for en route traffic management through Monte Carlo simulations. Other literature suggests the need for a probabilistic description of weather for strategic Traffic Flow Management applications (Mitchell, et al., 2006, Sheth, et al. 2007) and a better temporal resolution for ATM strategic planning (Chan 2006). The studies conducted so far have used probabilistic weather as a model, because operational products, other than the broad-coverage CCFP, are not available. When strategic and operational probabilistic forecast products are available (e.g., Localized Aviation MOS (Model Output Statistics) Product (LAMP), Ghirardelli and Glahn (2010)), research will need to be conducted to assess the corresponding reduction in airspace capacity. A recent research by Klein (2008) has shown that a probability threshold value is required for the airspace capacity estimation. Then, the threshold value can be used for efficient flight routing, especially, for the Center level weather events.

The current study presents a method for using probabilistic convective weather forecasts for strategic air traffic flow management decisions. First, the experimental 6-hour National Convective Weather Forecast (NCWF) probabilistic data product was chosen and integrated in an ATM simulation environment. Flight tracks were superimposed on NCWF probability of level 3 or higher Vertically Integrated Liquid (VIL) contours for each of the forecasts. The aircraft deviations around the actual severe weather and the forecasted probabilities were noted. Based on the *maximum* value of probability each flight skirted around, the Probability Threshold Parameter (PTP) was derived. Once the PTP values were available, a method is suggested for using it in flight routing decisions. To accomplish this, alternate route strategies were analyzed for a scenario when severe weather closes the Bonham (BYP) arrival fix for the Dallas/Ft. Worth International (DFW) airport. Thus, first this paper presents an approach for generating the threshold parameter, and then a method to apply it for flight routing decisions in a local weather scenario.

The simulation environment used to synchronize convective weather forecasts and air traffic data is described in Section 2. The method to obtain the PTP for the entire National Airspace System, the 20 Centers in the Continental US, and values for seven high-altitude sectors of interest in ZFW is presented in Section 3. The need for using local rerouting is described and a suitable implementation is detailed in Section 4. Results for a specific weather scenario in ZFW are also displayed in that Section. The paper ends with concluding remarks in Section 5.

2. Integration of weather and air traffic data

In order to study the impact of convective weather on air traffic, a simulation with integrated traffic and weather information is needed. The Future ATM Concepts Evaluation Tool (FACET) (Bilimoria, et al. 2001) provides that capability. FACET is a simulation and modeling environment developed to explore advanced ATM concepts. It handles traffic information at various levels in the NAS, from Centers and the sub-regions of Sectors, to the capability of modeling and assessing individual aircraft trajectories. FACET can be run in playback mode to understand how the air traffic evolved on a particular day by replaying recorded data. FACET processes the FAA's Enhanced Traffic Management System (ETMS) air traffic data and various convective weather products, such as the Corridor Integrated Weather System (CIWS), Collaborative Convective Forecast Product (CCFP), National Convective Weather Forecast (NCWF), and Next Generation Radar (NEXRAD). Integration of newer convective weather products like Collaborative Storm Prediction for Aviation (CoSPA) (Wolfson, et al. 2008) and Localized Aviation MOS (Model Output Statistics) Program (LAMP) (Charba and Samplansky, 2009) are also available within FACET. The integrated information can be used for visualizing the effects of weather in real time, as well as for planning of flights around forecasted weather.

The NCWF-6 data provide one-, two-, three-, four-, five- and six-hour weather forecasts of VIL level 3 or higher with a continuous probability distribution of severe weather every 15 minutes. Figure 1 shows a snapshot of the synchronized air traffic and convective weather data displayed in FACET for 5 pm Central Daylight Time (CDT) or 22:00 Coordinated Universal Time (UTC) on July 10, 2007. The Ft. Worth (ZFW) ARTCC (closed polygon in the center, in white) is shown with a number of important fixes (circled) in the region. These are: Tulsa (TUL) and Will Rogers (IRW) in the north, Monroe (MLU) in the east, Waco (ACT) in the south, Wink (INK) in the west, etc.) along with four DFW arrival fixes of Cedar Creek (CQY) (southeast), Glen Rose (JEN) (southwest), Bowie (UKW) (northwest) and Bonham (BYP), hidden under weather, in the northeast. The one-hour NCWF-6 forecast data published at 4 pm CDT are shown as filled polygons. The color for weather forecast data is continuously varying, and the probability of convective weather varies from 25% (cyan) on the periphery to 100% (dark red) at the center. Convective weather observations from NEXRAD are shown as unfilled contours of VIL level 3, 4, 5, and 6 in yellow, orange, red and dark brown, respectively. The aircraft arriving at and departing from DFW are shown as pink and cyan dots, respectively, along with their 20-minute track histories. It is observed from this figure that the track histories indicate flight deviation around weather, as seen just northeast of DFW airport.

3. Probability Threshold Parameter

For each aircraft track, the location and height of aircraft were used to find the corresponding grid cell in the forecast data. If an aircraft was flying below the forecasted probability ceiling, and its location was contained within a 10% or higher probability contour, then the aircraft was considered traversing through the probability field of the forecast data. For each aircraft's flight from origin to destination, the maximum probability value of VIL level 3 or higher was recorded. These data are recorded only if the probability forecast was valid at the time of aircraft track and only if at that location a storm ceiling (echo top) value was available (see Dupree, et al., 2006).

In Fig. 2a, a simulated flight on its FAA-filed flight plan on May 16, 2007 is shown with a yellow triangle for ACID1. As seen in the data block, the aircraft is flying from Norfolk, VA (ORF) to Indianapolis, IN (IND) at 32,000 ft (or Flight Level FL 320). It's traversing through a one-hour forecasted convective weather polygon. As can be seen from Fig. 2a, the ACID1 path traverses the predicted weather probability field between the 03:12 and 03:20 UTC (10:12 and 10:20 pm CDT) times shown with white arrows. While crossing the weather contours, it traverses the NCWF-6 continuous probability distribution from 0% at 03:00 UTC (10:00 pm CDT) to about 70% at 03:15 UTC (10:15 pm CDT), as shown in Fig. 2b. Figure 2c shows how the actual flown aircraft tracks completely avoid the weather, and so the probability traversal curve would have all zero values. It should be noted that actual severe weather on that day closely represented the forecasted weather, as shown in Fig. 2d. The probability traversal profile, like the one in Fig. 2b for the simulated flight, is created for all actual flights to study flight deviation behavior.

The *maximum* probability value crossed by each flight is recorded and binned in a reverse cumulative histogram ranging from 100% to 10% in 1% decrements. The 80th percentile number of this histogram, similar to the one proposed by Chan, et al., 2007 and DeLaura et al. (2009), is then used to determine the Probability Threshold Parameter (PTP) value. Since the PTP value is clearly avoided by a large number of aircraft, it is used as the weather probability value to avoid for flight routing decisions.

Figure 3a shows the scatter plot of the probabilities with the aircraft altitudes using ETMS data for one instant of time (08:12 am CDT) on May 16, 2007 and a one-hour forecast. In the scatter plot with a total of 48 flights plotted, there are 8 aircraft with values above 35% probability. It was important to analyze if the aircraft were really traversing through 40% to 65% probability values, because they could encounter significant convective activity. Analyzing their tracks, it was found that six of these eight aircraft were either transitioning (climbing or descending) aircraft or intruding a higher probability contour for one time instant. This may also be the situation when aircraft venture into the severe weather region or could be airline-designated pathfinder missions. It should be noted that the current analysis might show aircraft in higher probability regions due to forecast location error, intensity inaccuracies and flight track data errors. Figures 3b, c, d, and e show the altitude versus maximum probability data accumulated for one- through four-hour forecast valid-time instances for May 16 through 22,

2007. In this analysis, inconsequential low probability values (below 10%) were ignored, hence, the blank region in Fig. 3a through 3e, to the left of 10%. As can be seen from Figs. 3b through 3e, the maximum observed probabilities for level 3 or higher convection decrease with time forecast horizon. A vertical line shows this at 99%, 83%, 58% and 43% in the one-, two-, three-, and four-hour data sets. This reduction in maximum probabilities is a result of the blending process used in the generation of these forecasts, described in Germann and Zawadzki (2000), Weygandt, et al. (2004), Megenhardt, et al. (2004), and Pinto, et al. (2008). The maximum observed probabilities for the five- and six-hour forecasts were below 30%, and were discarded. Even the three- and four-hour values were lower fidelity. Therefore, for the rest of this paper, only one- and two-hour results are presented for the threshold value computation.

a. Probability Threshold Parameter for the NAS

The reverse cumulative histograms of number of aircraft at different altitudes traversing through the weather probability field are shown in Fig. 4 for (a) one- and (b) two-hour forecasts. For each of the curves going from ground level up to FL 400, it was observed that for a one-hour forecast, the 80^{th} percentile value resides at about 33% (Fig. 4a). The colored vertical lines corresponding to various 10,000 ft blocks of altitude demonstrate this. The corresponding value for two-hour forecasts was about 23% (See Fig. 4b). For the purpose of this research, the 80^{th} percentile value was chosen as the Probability Threshold Parameter (PTP). Aircraft are generally observed to go around probability values higher than the PTP. The flow management and flight planning decision-makers can use this value of PTP to generally avoid regions of forecasted severe weather.

Further analysis of the data provided weather traversal characteristics as a function of airlines and aircraft types. These results are presented in Fig. 4c and 4d. It should be noted that these probabilistic weather data are only used in this post-processing analysis and were not available to operators. From one-hour data presented in Fig. 4a, the top four aircraft operator occurrences are presented in Fig. 4c. From the same data set, the top four aircraft type occurrences are shown in Fig. 4d. The four most frequently found aircraft types are the Boeing B73x, the Airbus A31x, the McDonnell-Douglas MD8x, and the Canadair Regional Jet CRJx. All considered aircraft types are observed to avoid flying beyond about 35% probability (the 80th percentile value). Similarly, as seen from Fig. 4c, major airlines appear to deviate beyond the ~35% probability value. Therefore, the NAS PTP value was concluded to be 35% for one-hour forecasts and 25% for two-hour forecasts.

b. Center-based Probability Threshold Parameter

In this study, the PTP value was derived for each of the 20 NAS Centers as well. The purpose of evaluating the PTP value for each Center was to identify if there was a difference based on Centers. Figures 5a and 5b show the behavior of aircraft traversal for each of the 20 Centers for the one- and two-hour forecasts. These data were recorded for all aircraft flying between 10,000 and 40,000 ft. It is seen from the one-hour plot on left that Ft. Worth (ZFW), Houston (ZHU), Atlanta (ZTL), Jacksonville (ZJX), and Miami (ZMA) Centers (all five neighbors in the southeastern part of the US) show large number of aircraft traversing through higher probability values. It is also seen from Fig. 5a that there are three bands within which the data can be classified. The first one consists of those five southeast Centers, ZFW, ZHU, ZTL, ZJX and ZMA, with larger than 40,000 aircraft crossing the 10% intensity contours, above the upper brown bar shown on the y-axis. The third consists of less than 10,000 aircraft crossing the 10% intensity contours, below the lower brown bar. These are the 4 western Centers, Los Angeles (ZLA), Oakland (ZOA), Seattle (ZSE) and Salt Lake (ZLC), where there’s less convective activity generally. The middle band between the two brown bars consists of the 11 remaining Centers showing between 10,000 and 40,000 aircraft. From Fig. 5b for the two-hour forecasts, similar banded behavior is observed, with the same Center members, but the middle band has between 20,000 and 70,000 aircraft. As noted earlier, the probability threshold values decrease (due to increased uncertainty) with increase in forecast time, which explains the curves steepening to the left. The computed PTP values for the one-hour forecasts were as follows: the minimum value was 18% (from the lower band Centers), the maximum value was 33% (from the upper band Centers), the median was 33% and the average was 29% for all Centers. For the two-hour forecasts, the values were 13%, 23%, 23% and 20%, respectively.

In order to understand the traversal trend around forecasted weather probabilities, the numbers of grid cells with 10% or higher forecast probability value were computed for the entire four-month one- and two-hour NCWF-6 forecast data set. The NCWF-6 has a 2 nmi grid resolution, which implies that over the continental United States, there are over 1 million grid cells. The numbers for one-hour weather forecasts are presented at left, and the two-hour results are presented at right in Fig. 5c and 5d. With the exclusion of Atlanta Center and inclusion of Minneapolis Center, each of the five upper band Centers has the most number of >10% probability value cells. This suggests that those five Centers experienced most convective weather (at least for the data under consideration.) It should also be noted that for PTP computation to be relevant, existence of large number of weather cells (over 100,000 for 10% value), as well as high air traffic is necessary.

c. Fort Worth Center (ZFW) Threshold Parameter

For this study, Ft. Worth Center was selected for further evaluation due to relatively high convective weather presence, its central location in the NAS and observed probability traversal data. Figures 6a through 6d show the results for ZFW for different parameters for a one-hour forecast, four-month data set. Figure 6a shows the number of aircraft at various altitudes starting from ground level up to flight level (FL) 400 in 10,000 ft increments. It is observed that more aircraft in the ZFW region traverse the probabilities in the lowest 10,000 ft (closer to the Terminal Radar Approach Control or TRACON), and between flight levels 300 and 400. In the FL 100-200 range, aircraft fly visual flight rules. In the FL 200 to 300 range, mostly regional jets are present. The overflights largely fly through the Center between FL 300-400. In the FL 100-200 and FL 200-300 ranges, 28% PTP was observed (shown by vertical lines in the figures) while in FL 0-100 and 300-400 altitude bands, PTP values of 30-32% were observed. Fig. 6b shows results for the time of day statistics. The convective weather usually appears in the afternoon through evening hours. The 7 am through 1 pm CDT (12-18 UTC) and 1 pm through 7 pm CDT (18-24 UTC) times see intermediate probability traversal activity (PTP=30%). The 7 pm through 1 am CDT (00-06 UTC) sees lower PTP of 28%, as there is lesser traffic and lower convective activity in the atmosphere. It is seen from the purple curve that the hours of 1 am through 7 am CDT (06-12 UTC) show PTP of 31% when there is minimal traffic activity.

Additionally, the behavior of different airlines and aircraft types was also studied. Figure 6c shows the behavior of four dominant airlines in the Ft. Worth Center. All 4 Airlines were avoiding between 28 and 30% probability values. Airlines 1 and 3 have DFW as the hub while the other two do not. Rhoda, et al. (2002) showed that pilots tend to venture into convective activity more, when they are closer to destination. On the other hand, Fig. 6d shows the number of aircraft crossing probability values for the four aircraft types in the center. The main observation was that the MD8x aircraft (green) appear to avoid the 28% contour value, but the three other aircraft types were avoiding the 32% intensity contours.

The two-hour forecast data were processed as well and all the graphs showed similar behavior to the one-hour cases. For altitudes between FL 100-200 and FL 200-300, 18% PTP was observed, while all other altitude bands showed a PTP of 23%. For the 11 am to 11 pm CDT (18-24 and 0-6 UTC) a 23% PTP value was observed while the remaining times of 11 pm to 11 am CDT (6-12 and 12-18 UTC), it was 18%. The airline behavior was similar with the top two DFW users showing 18% while the other two users had 23% PTP value. Following a similar trend to one-hour forecasts, MD8x showed 18% PTP while the others were avoiding 23% intensity contours.

d. Probability Threshold Parameter for Sectors in Fort Worth Center

In order to study the impact of weather in the Ft. Worth Center, PTP value in various Sectors were computed. Figure 7 presents all the high-altitude sectors (all at and above FL 240) in the Ft. Worth Center. The 7 sectors for which data are presented in Table 1 are highlighted in cyan in Fig. 7. These seven sectors contain the four main arrival fixes (shown in yellow) and have more complex traffic patterns (e.g., transitioning and merging) in the Center. Other ZFW sectors have lower traffic complexity. Table 1 shows the one- and two-hour forecast (comma-separated) PTP values. PTP values from FL 240-400 are shown in row 1. Data in other rows are for times of day, airlines and aircraft types. It is worth noting that sector ZFW86 has a complex traffic pattern due to arrivals from the east, departures from the south (Houston Center airports) and multi-directional overflights. It can be observed that mostly ZFW86 has a PTP value, which on average is at or above other sectors for the altitude range shown. The highest one-hour PTP value noted is for aircraft-type 4 with 36% in ZFW42, while the lowest one-hour PTP value is 14% in ZFW46 between 6-12 UTC (1 to 7 am CDT) when there’s almost no convective weather and low arrival or overflight traffic. For all ZFW sectors, one-hour values lie between 27 and

32% with a 30% average, while the two-hour values lie between 17 and 21%, with a 20% average. Overall, the average 30% (one-hour) and 20% (two-hour) values for this large case are valid across all airlines, aircraft types, altitudes and times of day. Since the Sector level values are close to the Center PTP values, additional Sector level analysis was not deemed necessary to study aggregate behavior of aircraft streams. A similar analysis can be conducted for three- through six-hour forecasts but was not done due to widespread low forecast probability values (see Fig. 3d and 3e).

4. Flight routing decisions

When severe weather is forecasted, various options for filing flight plans are available to airspace users (e.g., Airline Operations Center flight dispatcher) for routing their flights around or away from regions of severe weather. These include the use of FAA's Severe Weather Avoidance Plan (SWAP or Playbook) Routes, Coded Departure Routes (CDRs), historic flight plan databases, individual airline's Preferred Routes, etc. A dispatcher often has to determine if their flight is going to be moved due to weather or congestion (Sridhar, et al. 2002, Sridhar, et al. 2005). On the other hand, a Traffic Management Coordinator's perspective is to maintain a safe and efficient flow of traffic through their Center with minimal delays and congestion. Aspects of flight routing decision processes are considered in this Section. Results presented in previous sections help in better decision-making during severe weather events.

a. Local Reroutes

During the times when severe weather is predicted to occur, it obviously benefits the operators and users to assess the impact on air traffic. For both the parties, it is useful to have a capability to evaluate possible rerouting options. Such a system should have Center-level routing strategies available for a local weather event.

Once the probability threshold values have been computed as described earlier, various route options can be analyzed to assess the balance of demand and capacity. For example, if a fix for arrival traffic (e.g., Bonham, BYP, see Fig. 8) for DFW airport or overflight traffic transitioning through the ZFW Center is forecasted to be under convective weather in the next one- through six-hours, which reroutes can be employed? Which route options can be utilized to maintain the stream of aircraft flowing without major schedule disruption and minimal additional workload for controllers, while providing sufficient predictability? In general, Playbook routes at the national level will impact a large number of aircraft, with associated potential loss of schedule integrity. For local weather scenarios of a Center-level scope, it is desired that the impact on other Centers be minimized. The proposal is to reduce the burden on other Centers while the impacted Center works cooperatively with the Air Traffic Control System Command Center (ATCSCC). Depending on the situation, traffic managers could employ a local method, a national strategy, or a hierarchical approach.

A local Center-based rerouting what-if analysis capability is presented, in which the affected Centers can employ local and predefined routes for assessing the impact of various strategies, in coordination with the ATCSCC. While implementing the National Playbook, generally the aircraft's flight plan is often modified from origin to destination, resulting in larger deviation from nominal operations for better system predictability. The concept of Center Routes proposed here, keeps the flight plan unchanged until the point of entry into the weather impacted Center. The flight plan is changed only after the last fix before entering the affected Center, with the planned local reroute up to the destination (for arrivals) or exit from Center (for overflights). This provides a level of predictability (assuming a satisfactory level of forecast accuracy) to the dispatcher as well as the traffic manager. It also eliminates the need to route each aircraft individually and maintains the traffic stream. Since the probabilistic convective weather data are available up to six hours in advance, such strategies could constantly be evaluated for air traffic management planning decisions in the long term.

b. ZFW Scenario

Traffic enters Ft. Worth Center (ZFW) from four neighbors. Figure 8 (a) shows that the traffic from Albuquerque Center (at left) mainly enters ZFW through Texico (TXO) and Panhandle (PNH); from Kansas City (ZKC) Center (above) through Tulsa (TUL); from Memphis (ZME) Center (at right) through Little Rock (LIT), Ft. Smith (FSM) and Munroe (MLU); and from Houston (ZHU) Center (below) through Alexandria (AEX) and GIFFA fixes. In this study, local routes were designed for the scenario where one of the arrival fixes (e.g., Bonham, BYP) was closed, as in the events of July 10, 2007. Consider a flight plan for an aircraft arriving from Chicago O'Hare International Airport (ORD), routinely filed with the FAA as ORD..RBS..SGF..BYP.BYP5 .DFW. In this implementation, the route would be modified, for example, as ORD..RBS..SGF..TUL..IRW..UKW.UKW9.DFW, using a potential route option incorporating alternate fixes and a non-impacted arrival fix Bowie (UKW). Once these routes were designed for arrivals into DFW, what-if analyses were conducted to study the impact on flights. Metrics of delay, congestion, additional fuel, and distance were then computed.

c. Results of Local Rerouting

Figure 8 presents a scenario when BYP (the northeast arrival fix for DFW) is closed, as was the case on July 10, 2007 with significant delays for DFW arrivals. The PTP values computed earlier were used to look at the area covered by one-hour forecast 30% probability values over the BYP arrival fix. The traffic originally planned to arrive through BYP from various northeastern origin airports is rerouted along TUL, IRW, SPS and UKW to arrive into

DFW. Figure 8 shows the situation before (Fig. 8a) and after (Fig. 8b, routing through IRW) implementation of the local reroutes through ZFW. Cyan lines show flights that were to arrive at DFW through BYP, magenta lines show arrivals through UKW and green lines are arrivals through CQY. The reroutes for this BYP closure scenario were implemented using three different strategies, which would depend on the location and spread of predicted weather. First strategy rerouted aircraft to ADM and UKW to arrive into DFW (not shown in Fig. 8 to avoid clutter). The second strategy rerouted through IRW and UKW (Fig. 8b); while the last strategy rerouted aircraft even further to go from IRW, SPS and UKW to arrive into DFW (again, not shown in Fig. 8 to avoid clutter). In each of the three strategies, aircraft coming from Ft. Smith (FSM) and north of it (upper cyan arrival stream in Fig. 8a) were diverted to the ADM arrival stream. The aircraft coming from Little Rock (LIT) and southeast of it (lower cyan arrival stream in Fig. 8a) were routed through Belcher (EIC) and Cedar Creek (CQY) into DFW. These can be observed by contrasting Figs. 8a and 8b. The lower arrival stream (EIC..CQY..DFW) flight reroutes were held constant in each of the three strategies.

In order to understand how effective these routes are and what the impact on traffic is, results are presented for each of the three strategies in Table 2. It shows the effect of each strategy as applicable to a different weather impact and coverage scenario. The reroutes were implemented in FACET for a four-hour period from 3 to 7 pm CDT (20 to 24 UTC) using traffic data from July 24, 2007. The data from July 10, 2007 (a Tuesday) would be corrupted with controller input of rerouting the aircraft due to presence of convective weather over BYP. Therefore, traffic data from July 24, 2007 (another clear weather Tuesday) and convective weather data from July 10, 2007 were used for simulating reroutes. In each of the three cases, the number of impacted flights was 155. Table 2 provides the metrics for each of the three strategies.

The aircraft incurred an average of 12, 15 and 18 minutes of delay; 794, 1,012 and 1,235 pounds of additional fuel; and 42, 54 and 66 nmi additional distance, per aircraft for the three strategies, respectively. It is worth noting that in each of the three cases, there was no congestion (number of aircraft above Monitor Alert Parameter) observed in the northwestern sector ZFW47 (where UKW lies) or in the southeastern sector ZFW89 (where CQY lies). This behavior is observed mainly due to a smaller number of aircraft present during the evaluation interval. However, this suggests that rerouting flights to the same region of airspace may not necessarily overload the airspace but may provide a reasonable alternative to dealing with the weather problem.

The last column in Table 2 corresponds to the implementation of the FAA-published Playbook route, DFW_BYP1, for arrivals into DFW airport during a BYP closure event. The result indicates that 218 DFW arrivals are affected. A leading cause for a larger number of flights impacted is that the current description of DFW_BYP1 modifies flights not only flying over BYP, but also over other arrival fixes, CQY and JEN. The use of DFW_BYP1 does not include other flights (e.g., overflights or arrivals at other airports) in the Center and separate Playbook routes need to be implemented to account for those flights. In the local rerouting concept proposed and implemented here, flights flying over BYP, either arriving at DFW, DAL, Houston (Intercontinental, IAH and Hobby, HOU), or other nearby airports like San Antonio (SAT), etc. were all accounted for with less than 10 minutes of flying time change. The DFW_BYP1 plan could start modifying flight routes up to two hours (or more) in advance. Figure 8c shows the scope of the DFW_BYP1 plan. The green lines show the flight plan amendment that would be used for aircraft arriving at DFW airport from origins across the northern and eastern part of the United States. The weather pattern shown is the same as in Fig. 8b. It is clear from Figs. 8b and 8c that the scope of local rerouting is smaller and less impact is felt by air traffic compared to the larger DFW_BYP1 or similar plan, especially for a convective weather problem of a local scope. It can be observed from Fig. 1 that on July 10, 2007, the aircraft from the north and east were arriving at DFW through IRW and SPS, which is closest to Strategy 3 implemented for this research.

It is acknowledged that for larger, multi-Center convective weather scenarios, the National Playbook provides appropriate rerouting and predictability. The capability of local reroutes proposed here address local weather events. The selection made by traffic managers of the strategy to implement depends largely on the involved traffic densities and timing of reroutes to be imposed along with other traffic management initiatives under consideration.

5. Conclusions

A method is presented for using probabilistic convective weather forecasts for air traffic management. Current air traffic and forecasted weather data are synchronized to obtain statistics of aircraft deviating around weather. A Probability Threshold Parameter (PTP) is derived, which represents the limiting value of probability that is largely avoided by aircraft. This quantitative metric is used to assess the probability contour that aircraft are observed to traverse in the vicinity of forecasted convective weather. The study provided threshold values for the National Airspace System (NAS) and all the 20 Centers in the Continental United States. The nominal PTP values for the NAS were computed as 35% and 25% for one- and two-hour forecasts, respectively. The corresponding values for the 20 Centers were 30% and 20% on average. It was observed that the 20 Centers are divided into three bands of small, medium, and large number of aircraft traversing around the forecasted probabilities. The Atlanta and New York Centers demonstrated higher number of aircraft flying through probability field with proportionately lower forecasted weather activity, while Minneapolis Center had higher weather occurrence but lower number of aircraft traversal through the probability field. The aircraft behavior in the Ft. Worth Center was further investigated in detail. The PTP values for different altitudes, times of day, airlines and aircraft types for Ft. Worth Center and seven high-altitude sectors therein are also presented. Most of the PTP values observed were in the vicinity of 30% and 20% for one- and two-hour forecasts, respectively.

Using the computed PTP values, a concept of Center-level rerouting is presented. Local reroutes were implemented in the FACET simulation environment for a rapid what-if analysis and estimation of impact on arrival and over-flights in a Center. Results for a specific scenario of the Dallas/Ft. Worth's Bonham (BYP) arrival fix closure are also presented. The metrics include arrival delay, additional fuel and distance, and congestion in the airspace due to rerouting. It was observed that the total impact on affected flights was smaller compared to larger scope National Playbook plan. In the suggested concept, the fewer flights were impacted and handled by locally impacted Center with no additional congestion.

Acknowledgments

The authors acknowledge discussions with Ms. C. Mueller, Ms. B. Brown, and Mr. J. Pinto of National Center for Atmospheric Research, Boulder, CO and with Mr. W. Chan and Dr. Shon Grabbe of NASA Ames Research Center. Sincere gratitude is also due to Mr. Rick Kervin, past Traffic Management Officer of Ft. Worth Center for his valuable opinions and sustained support.

References

Bilimoria, K. D., B. Sridhar, G. Chatterji, K. S, Sheth, and S. R. Grabbe (2001): Future ATM Concepts Evaluation Tool. Air Traffic Control Quarterly, Vol. 9, No. 1, March, pp. 1-20.

Chan, W. N. (2006): Considerations for Using Low Temporal Resolution Weather Information in Air Traffic Management, *6th Aviation Technology, Integration and Operations Conference*, Wichita, KS.

Chan, W. N., Refai, M., and DeLaura, R. (2007): An Approach to Verify a Model for Translating Convective Weather Information to Air Traffic Management Impact, *Proceedings of the AIAA Aircraft Technology, Integration and Operations*, Belfast, Northern Ireland.

Charba, J. P. and Samplatsky, F. G. (2009): Operational 2-H Thunderstorm Guidance Forecasts to 24 Hours on a 20-km Grid. *American Meteorological Society's 23rd Conference on Weather Analysis and Forecasting/19th Conference on Numerical Weather Prediction*. Omaha, NE, 15B.5.

Clifford, S. F., et al. (2003): Weather Forecasting Accuracy for FAA Traffic Flow Management, The National Academies Press, Washington DC, pp. 10-17.

DeLaura, R., and Evans, J. (2006): An Exploratory Study of Modeling Enroute Pilot Convective Storm Flight Deviation Behavior, *American Meteorological Society's 12th Aviation, Range and Aviation Meteorology*, Atlanta, GA, Paper 12.6.

DeLaura, R., B. Crowe, R. Ferris, J. Love, and W. Chan (2009): Comparing convective weather avoidance models and aircraft-based data. Aviation, Range and Aerospace Meteorology, Special Symposium on Weather Air Traffic Management Integration, Jan. 11-15, Phoenix, AZ, Amer. Met. Soc.

Dupree, W. J., M. Robinson, R. DeLaura, and P. Bieringer (2005): Echo Top Forecast Generation and Evaluation of Air Traffic Flow Management Needs in the National Airspace System. 12th Conference on Aviation, Range, and Aerospace Meteorology, January 2006, Atlanta, GA, Amer. Met. Soc.

Fahey, T. H., Phaneuf, T., Leber, W. S., Huberdeau, M., Morin, D. P., and Sims, D. (2006): Forecasts of Convection for Air Traffic Management Strategic Decision Making: Comparison of User Needs and Available Products, American Meteorological Society's 12th Aviation, Range and Aerospace Meteorology, Atlanta, GA, Paper 2.4.

Germann, U., and Zawadzki, I. (2002): Scale Dependence of the Predictability of Precipitation for Continental Radar Images, Part II: Probability Forecasts, *J. Appl. Meterol*., 43, 74-89.

Ghirardelli, J. E., Glahn, B., (2010): The Meteorological Development Laboratory's Aviation Weather Prediction System. *Weather Forecasting*, **25**, 1027–1051

Grabbe, S., B. Sridhar, and A. Mukherjee (2008): Sequential Traffic Flow Optimization with Tactical Flight Control Heuristics. AIAA Guidance, Navigation and Control Conference and Exhibit, Aug. 18-21, Honolulu, HI.

Hoffman, R., Krozel, J., and Jakobavits, R. (2004): Potential Benefits of Fix-Based Ground Delay Programs to Address Weather Constraints, AIAA Guidance, Navigation, and Control Conference, Providence, RI.

Klein, A. (2008): Airspace Availability Estimation for Traffic Flow Management using the Scanning Method. 27th Digital Avionics Systems Conference, Oct. 27-30, St. Paul, MN.

Matthews, M. P. and DeLaura, R. (2010): Assessment and Interpretation of En Route Weather Avoidance Fields from the Convective Weather Avoidance Model, 10th AIAA Aviation Technology, Integration, and Operations, Ft. Worth, TX.

Megenhardt, D., Mueller, C., Trier, S., Ahijevych, D., and Rehak, N. (2004): NCWF-2 Probabilistic Nowcasts, *American Meteorological Society's 11th Conference on Aviation Range and Aerospace Meteorology*, Hyannis, MA, Paper 5.2.

Mitchell, J. S. B., Polishchuk, V., and Krozel, J. (2006): Airspace Throughput Analysis Considering Stochastic Weather, *AIAA Guidance, Navigation, and Control Conference*, Keystone, CO.

Nilim, A. and L. El Ghaoui (2004): Algorithms for Air Traffic Flow Management under Stochastic Environments. Proceedings of the IEEE American Control Conference.

Pinto, J., H. Cai, G. Lee, J. W. Wilson, M. Steiner, R. Bullock, D. Albo, S. S. Weygandt, and C. L. Phillips (2008): Beyond Nowcasting of Thunderstorms: An Assessment of Various Blending Techniques for Increased Forecasting Skill at 2 - 6 h Lead Times. 13th Conference on Aviation, Range and Aerospace Meteorology, Jan. 21-24, New Orleans, LA, Amer. Met. Soc.

Rhoda, D. A., E. A. Kocab, and M. L. Pawlak (2002): Aircraft Encounters with Thunderstorms in Enroute vs Terminal Airspace Above Memphis, Tennessee. 10th Conference on Aviation, Range, and Aerospace Meteorology, May 13-16, Portland, OR, Amer. Met. Soc.

Sheth, K., B. Sridhar, and D. Mulfinger (2007): Application of Probabilistic Convective Weather Forecasts for Use in Air Traffic Management. 7th AIAA Aviation Technology, Integration and Operations Conference, Sep., Belfast, Northern Ireland.

Song, L., C. Wanke, D. Greenbaum, S. Zobell, and C. Jackson (2008): Methodologies for Estimating the Impact of Severe Weather on Airspace Capacity. 26th Congress of International Council of the Aeronautical Sciences (ICAS), Sep. 14-19, Anchorage, AK.

Sridhar, B., G. Chatterji, S. Grabbe, and K. Sheth (2002): Integration of Traffic Flow Management Decisions. AIAA Guidance, Navigation, and Control Conference, Aug. 5-8, Monterey, CA.

Sridhar, B., Sheth, K., Smith, P., and Leber, W. (2005): Migration of FACET from Simulation Environment to Dispatcher Decision Support System, *24th Digital Avionics Systems Conference*, Washington, D.C.

Sridhar, B and S. Swei (2007): Classification and Computation of Aggregate Delay Using Center-Based Weather Impacted Traffic Index. 7th AIAA Aviation Technology, Integration and Operations Conference, Sep., Belfast, Northern Ireland.

Steiner, M., C. K. Mueller, G. Davidson, and J. Krozel (2008): Integration of Probabilistic Weather Information with Air Traffic Management Decision Support Tools: A Conceptual Vision for the Future. 13th Conference on Aviation, Range and Aerospace Meteorology, Jan. 21-24, New Orleans, LA, Amer. Met. Soc.

Wanke, C. and D. Greenbaum (2007): Incremental, Probabilistic Decision Making for Enroute Traffic Management. 7th USA/Europe Seminar on Air Traffic Management Research and Development, Jul., Barcelona, Spain.

Weygandt, S. S., and Benjamin, S. G. (2004): RUC Model-Based Convective Probability Forecasts, *American Meteorological Society's 11th Conference on Aviation Range and Aerospace Meteorology*, Hyannis, MA, Paper 5.3.

Wolfson, M. M., W. J. Dupree, R. M. Rasmussen, M. Steiner, S. G. Benjamin, and S. S. Weygandt (2008): Consolidated Storm Prediction for Aviation (CoSPA). 13th Conference on Aviation, Range and Aerospace Meteorology, Jan. 21-24, 2008, New Orleans, LA, Amer. Met. Soc.

List of Figures

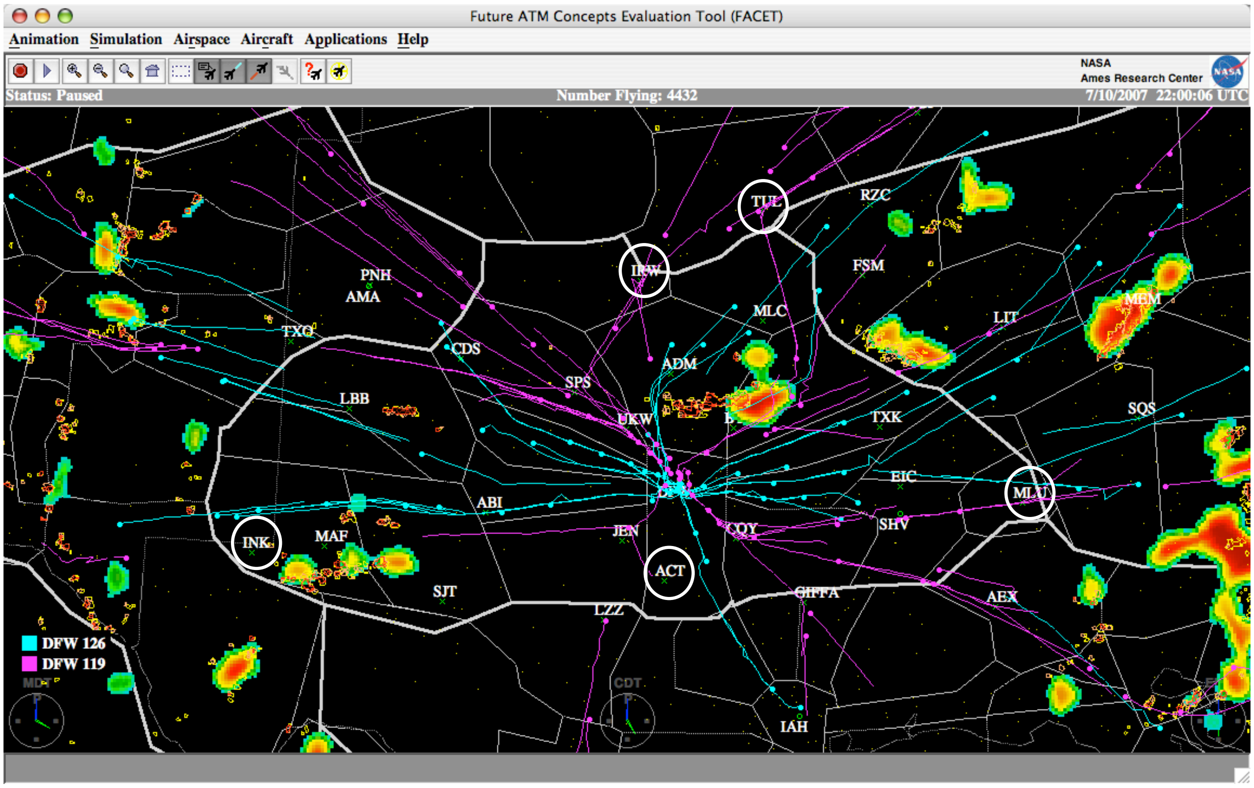


FIG. 1. Integrated display of air traffic and convective weather over Ft. Worth Center, shown with NCWF-6 probabilistic weather (filled) contours and NEXRAD weather contours. The pink and cyan dots represent arrivals to and departures from Dallas/Ft. Worth (DFW) airport with their 20-minute histories.

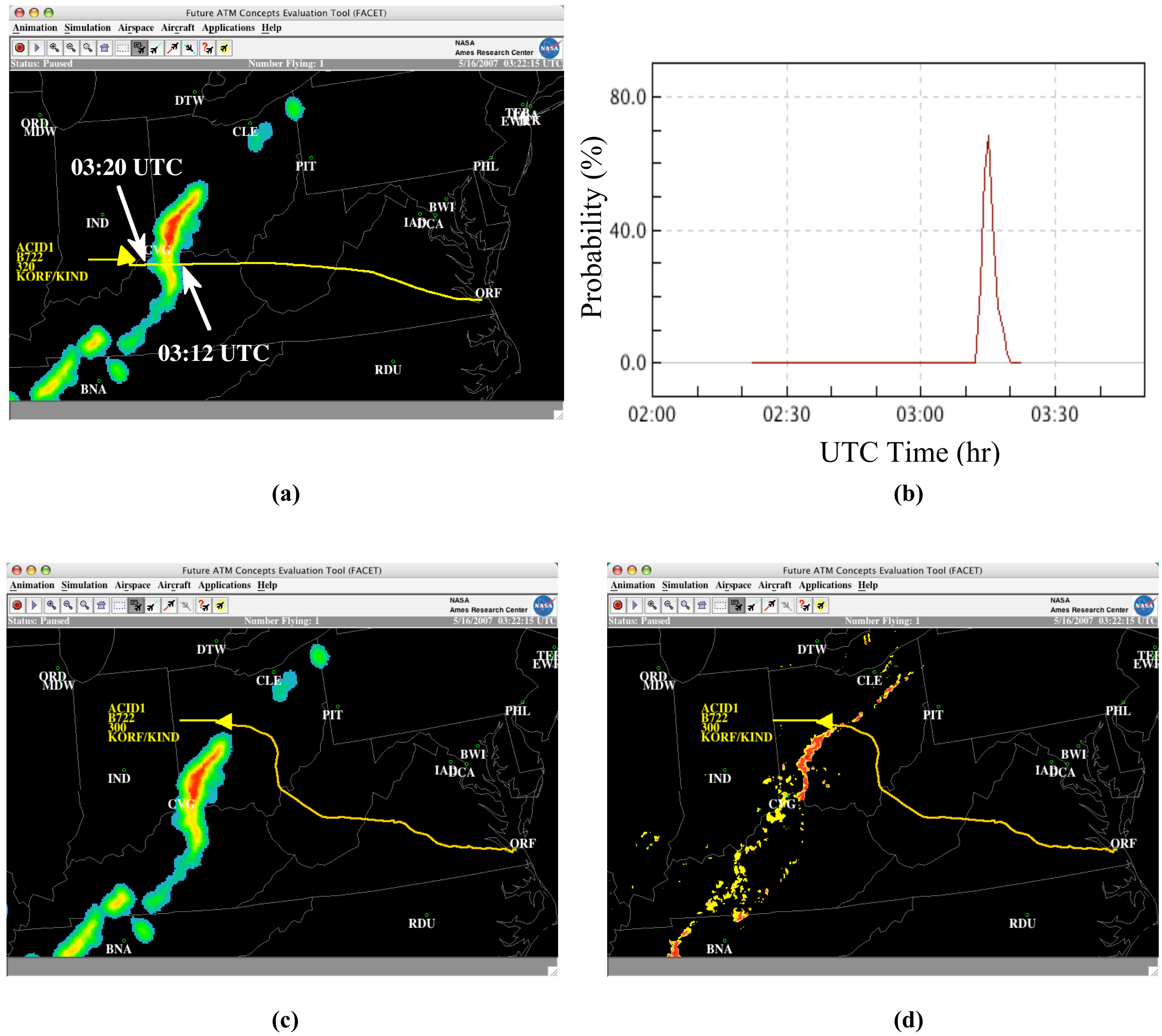


FIG. 2. (a) A simulated flight ACID1 going west to IND from ORF, traversing one-hour forecasted weather probability contours and corresponding probability contour traversal curve (b). Actual tracks for flight ACID1 with NCWF-6 probabilities (c) and NEXRAD weather (d).

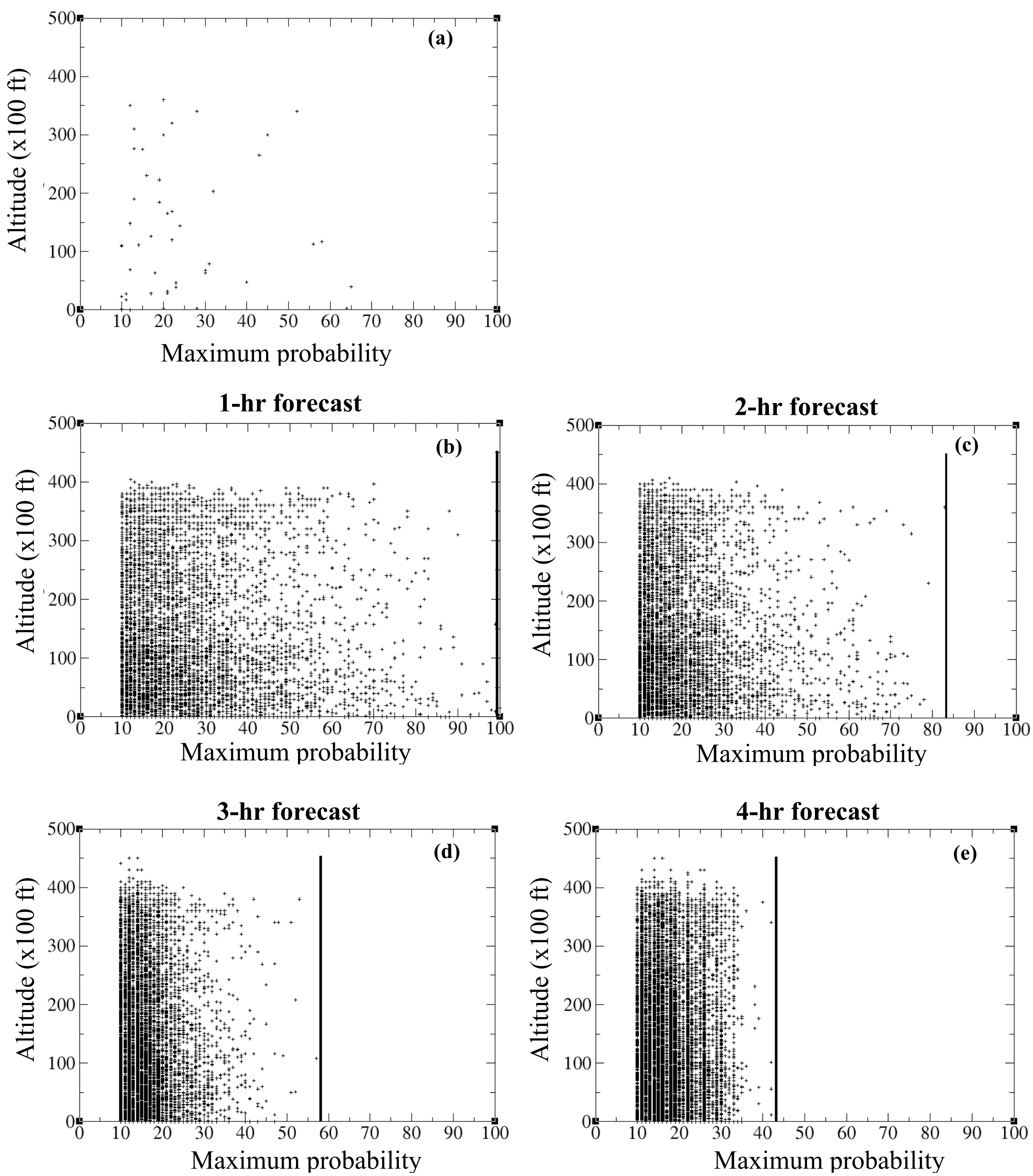
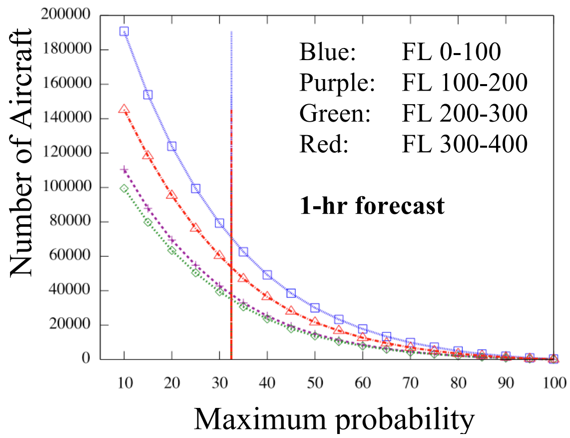
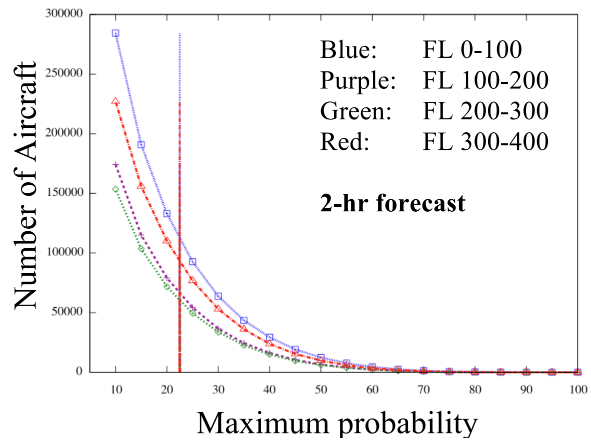


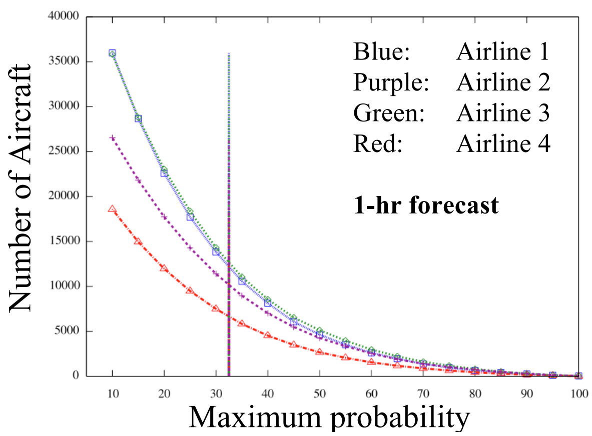
FIG. 3. The maximum encountered probabilities of all aircraft at various altitudes for one instant in time (a) and for (b) one-, (c) two-, (d) three-, and (e) four-hour forecasts.



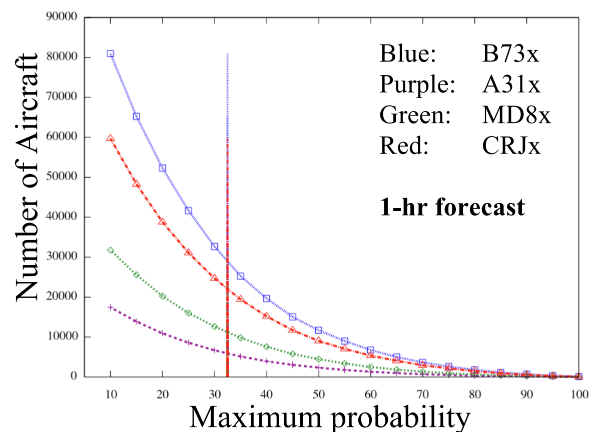
(a)



(b)



(c)



(d)

FIG. 4. Altitude probability curves for (a) one- and (b) two-hour forecasts. The probability curves for (c) four airlines and (d) four aircraft types for a one-hour forecast.

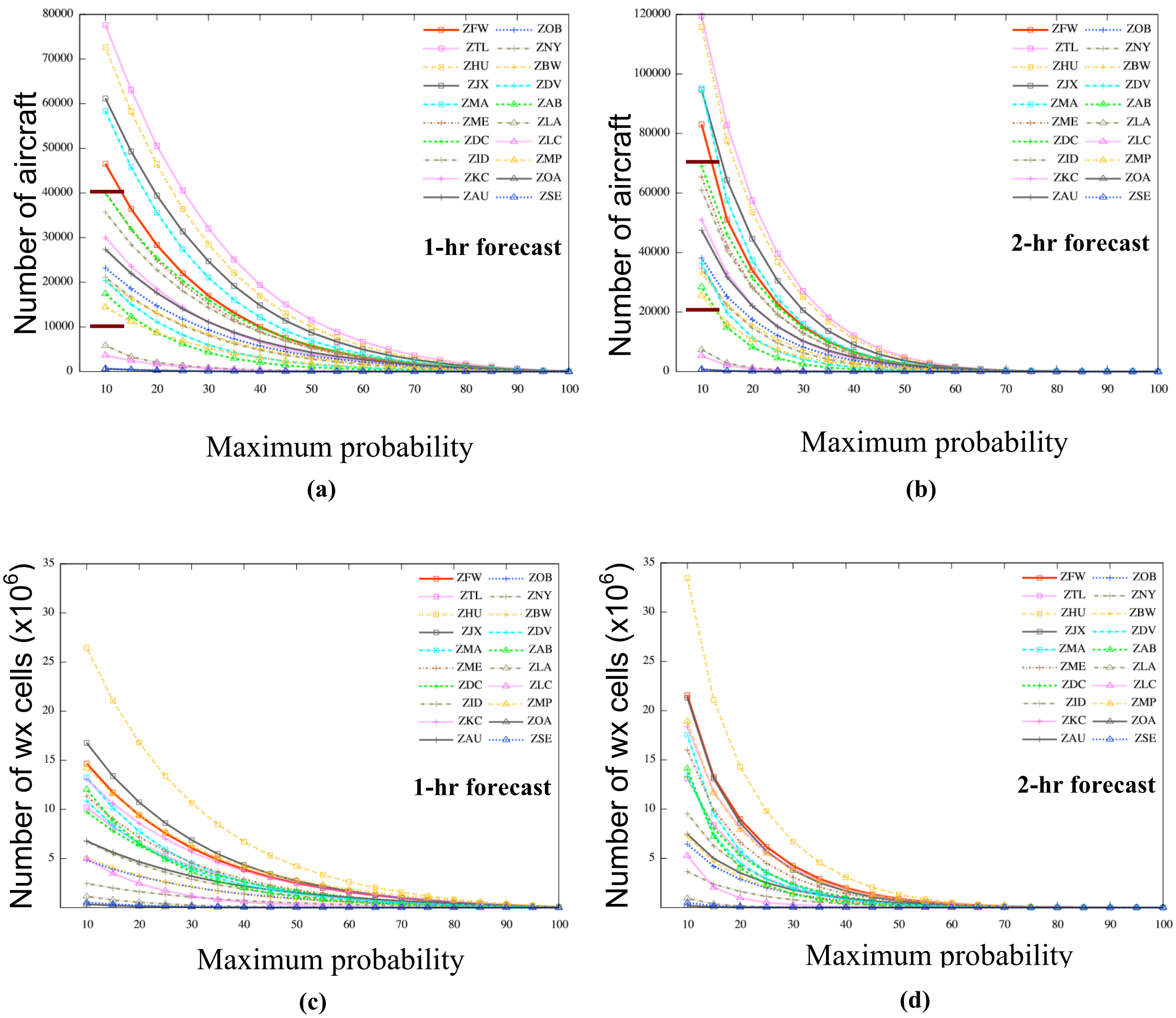


FIG. 5. Number of aircraft crossing maximum probability values for the 20 Centers in the continental United States for (a) one-hour and (b) two-hour forecasts over the four-month period. Number of convective weather cells in the 20 Centers for (c) one-hour and (d) two-hour forecasts over the four-month period.

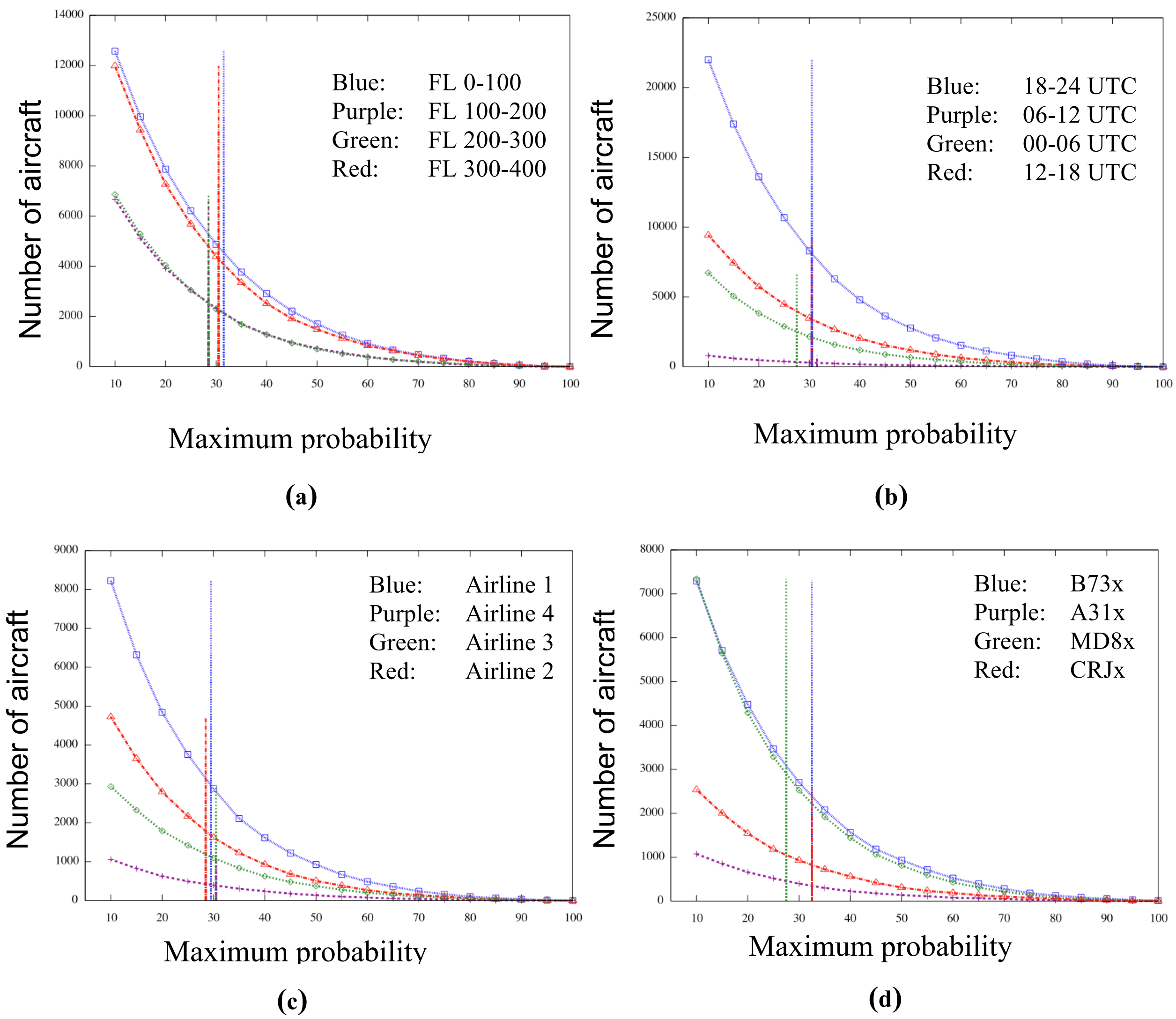


FIG. 6. Number of aircraft crossing one-hour maximum probability values for (a) four altitude ranges, (b) four times, for (c) four airlines, and (d) four aircraft types for Ft. Worth Center.

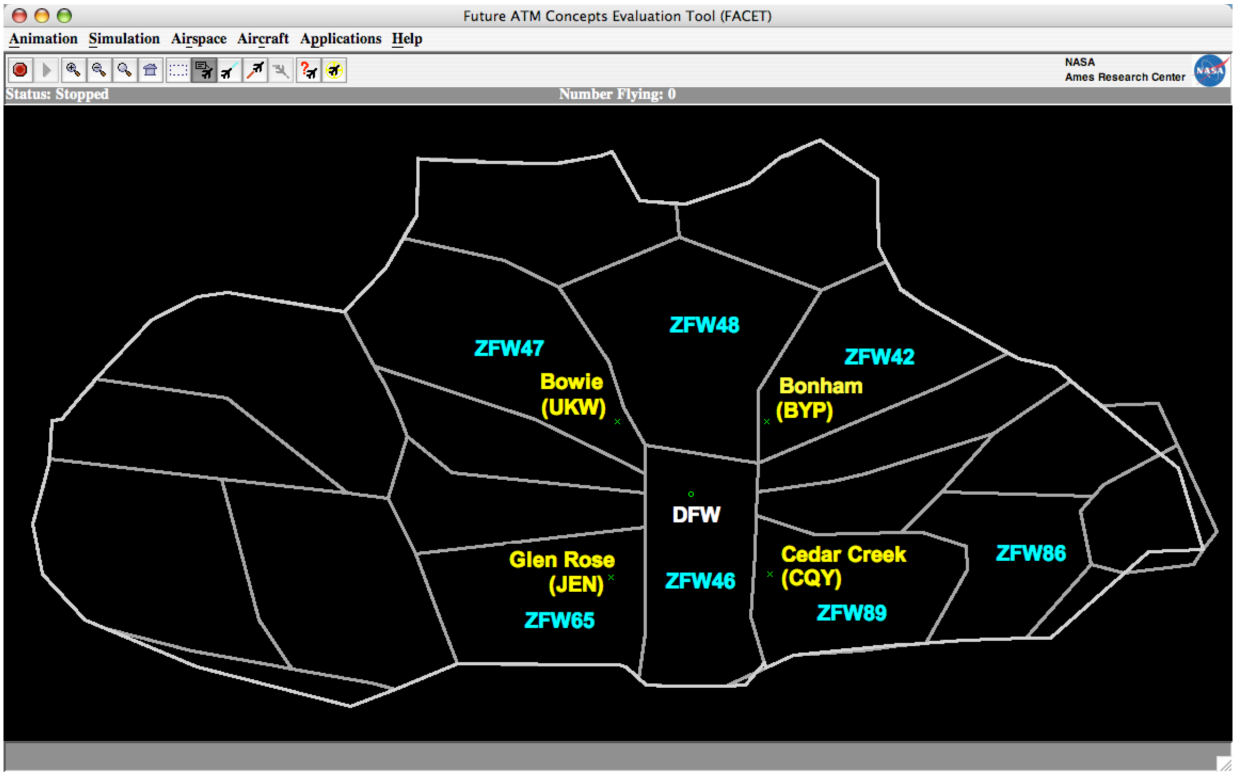


FIG. 7. ZFW Center with seven high-altitude sectors highlighted in cyan. The four main arrival fixes for DFW airport are highlighted in yellow.

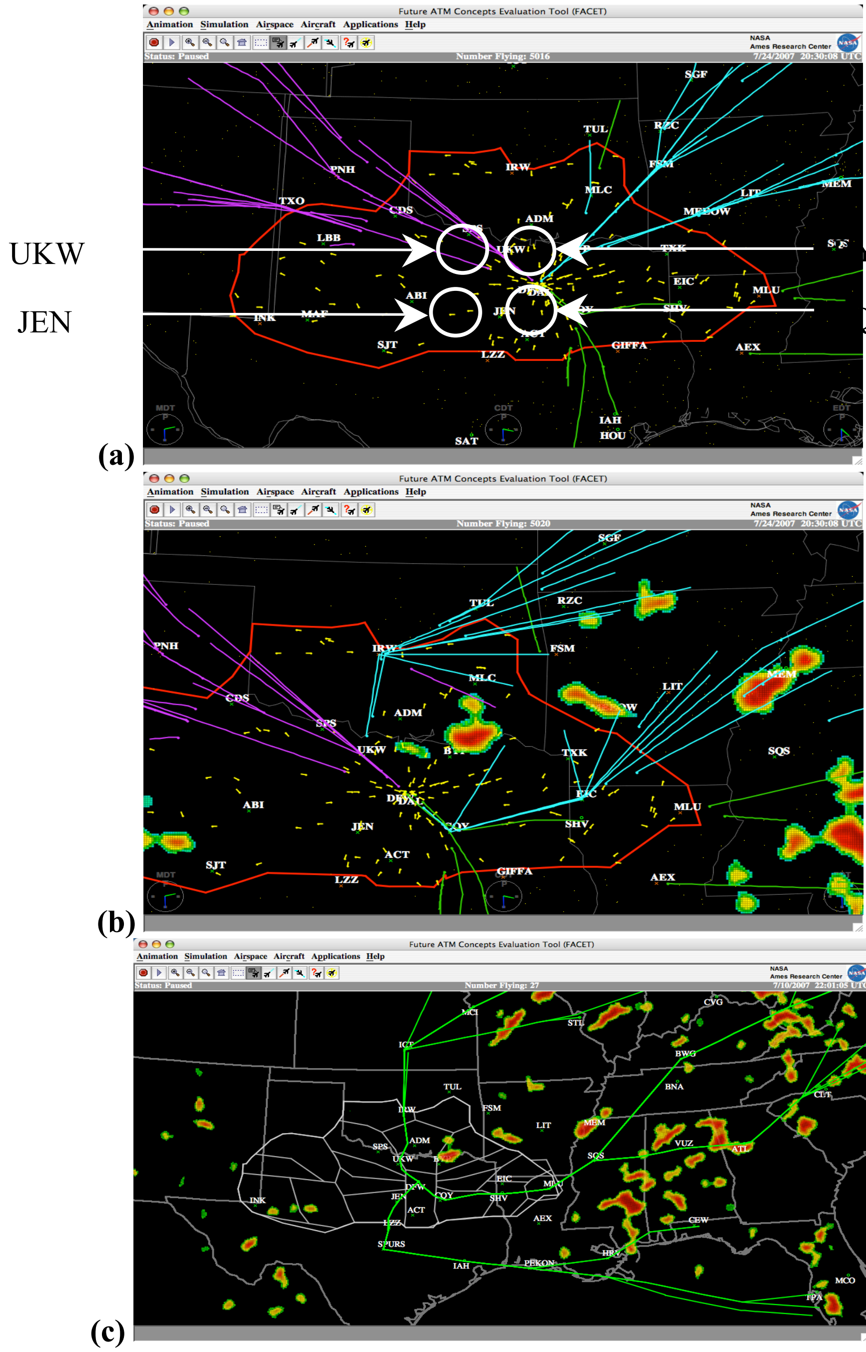


FIG. 8. (a) Original tracks of flights arriving into DFW through BYP (cyan), UKW (magenta) and CQY (green). (b) Result for Strategy 2 (route around IRW) is presented in Table 2. (c) Bonham fix closure for DFW arrivals using the DFW_BYP1 FAA Playbook route (green lines).

TABLE 1. The one- and two-hour forecast PTP values for seven sectors (shown in Fig. 6 above, counter clockwise) in ZFW.

Sector	ZFW47 (1hr,2hr)	ZFW48 (1hr,2hr)	ZFW42 (1hr,2hr)	ZFW86 (1hr,2hr)	ZFW89 (1hr,2hr)	ZFW46 (1hr,2hr)	ZFW65 (1hr,2hr)
FL: 240-400	28, 18	29, 19	30, 19	30, 21	29, 19	29, 19	28, 17
Time: 0-6	26, 18	30, 20	34, 21	30, 20	32, 20	30, 19	30, 18
Time: 6-12	32, 17	32, 18	33, 14	25, 23	27, 22	14, 15	32, 18
Time: 12-18	30, 19	30, 17	29, 18	28, 18	30, 16	24, 14	29, 19
Time: 18-24	28, 18	29, 19	28, 19	31, 21	27, 19	29, 19	27, 16
Airline 1	27, 17	28, 18	28, 19	29, 19	27, 19	31, 18	27, 18
Airline 2	25, 18	33, 20	27, 18	27, 18	27, 19	29, 19	25, 15
Airline 3	27, 19	30, 20	31, 20	29, 21	30, 19	28, 19	22, 19
Airline 4	28, 18	27, 20	31, 21	35, 20	32, 19	33, 19	27, 20
Aircraft type 1	28, 18	30, 19	29, 19	32, 21	29, 19	27, 19	24, 19
Aircraft type 2	28, 18	27, 18	29, 18	29, 19	27, 19	29, 18	27, 18
Aircraft type 3	29, 20	29, 19	29, 20	34, 21	30, 19	30, 17	28, 14
Aircraft type 4	32, 18	32, 19	36, 18	27, 21	24, 19	32, 20	28, 18

TABLE 2. The total delay, extra fuel and extra distance metrics for Bonham arrival fix closure, for the three rerouting strategies as well as the National Playbook plan simulation.

	Strategy1 (TUL.ADM. UKW)	Strategy2 (TUL.IRW. UKW)	Strategy3 (TUL.IRW.SPS. UKW)	DFW_BYP1 (Playbook route)
Number impacted flights	155	155	155	218
Total delay (min)	1,789	2,296	2,823	2,821
Total extra fuel (lbs)	123,108	156,992	191,388	185,833
Total extra distance (nmi)	6,520	8,343	10,287	13,186